

# QCD and High Energy Interactions: Moriond 2015 Theory Summary

G.ZANDERIGHI

*CERN, PH-TH, CH-1211 Geneva 23, Switzerland*

*and*

*Department of Physics, Theoretical Physics, 1 Keble Road, Oxford OX1 3NP, England*



I will summarise the new theory developments that emerged during the 2015 QCD Moriond conference. I will give my perspective on some of the topics and emphasise what I consider most relevant.

## 1 Introduction

We had more than 30 theory talks covering a rather broad range of topics. The theory talks were allocated to different sessions: Higgs and top, Flavour, QCD, the latter divided into more perturbative/technical aspects and more non-perturbative/formal developments, New Phenomena and Heavy Ions. Sections in this summary reflect the sessions we had at the conference.

## 2 Higgs and top

Remarkably, we had only one theory talk in the Higgs and top section.<sup>a</sup> Bernhard Mistlberger presented first N<sup>3</sup>LO results for the inclusive gluon-fusion Higgs cross section in the infinite top-mass effective theory.<sup>1</sup> This calculation is, in my opinion, the theory highlight of the meeting, hence I will spend few words on this topic.

In order to put this work into context, it is useful to examine the left panel of Fig. 1, which shows the slow perturbative convergence of the Higgs cross section. Furthermore, it is evident from the figure that the renormalisation (and factorisation) scale variation, that are commonly used to estimate theory uncertainties, underestimate the shift between different perturbative orders. Fig. 1 (right), presented at the general assembly meeting of the Higgs cross section working group in January,<sup>3</sup> shows results for the preferred total gluon-fusion cross section from different groups. Each group provided a prediction for the cross section obtained by using as a central renormalisation and factorisation scale choice  $m_H/2$  (light blue) and  $m_H$  (dark blue). The bands illustrate the scale uncertainty, obtained by varying renormalisation and factorisation

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<sup>a</sup>Next-to-next-to-leading order results for top-pair production were presented in the QCD session.

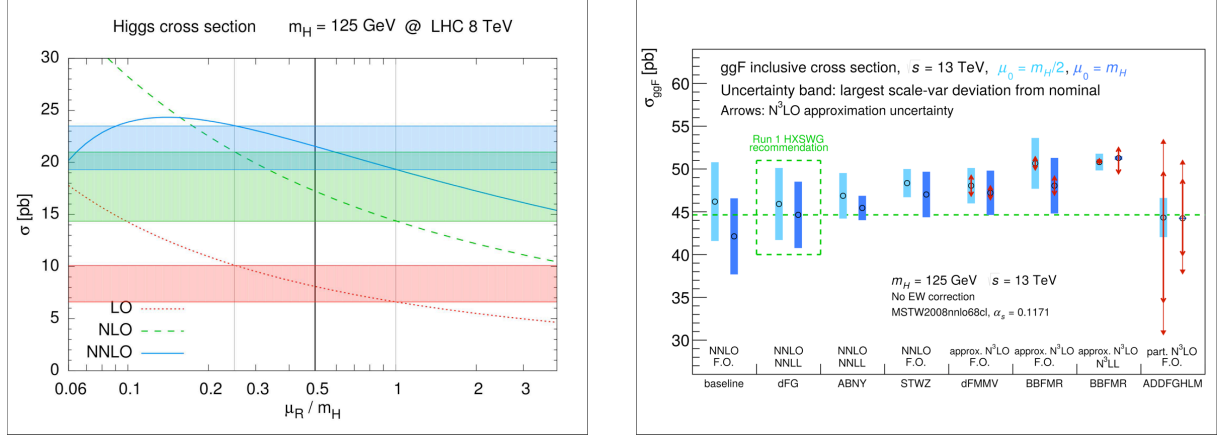


Figure 1 – Left plot: total gluon-fusion Higgs cross section at the LHC (8 TeV) as a function of the renormalisation scale at various orders in perturbation theory. The plot has been obtained using the code of ref. <sup>2</sup>. Right plot: a comparison of predictions for the total gluon-fusion Higgs cross section at the LHC (13 TeV) from various groups.

scales independently by a factor 2 (avoiding the variation where they differ by a factor 4), while the red errors denote the total uncertainty on the numbers as estimated by the groups. It is clear from the plot that there was no consensus on the size of the uncertainty on this cross section. This becomes particularly evident from the uncertainties quoted by the last two groups. However, the amount of perturbative control on this cross section has a direct impact on a range of new physics searches in the Higgs sector, hence it was crucial to improve on these predictions by computing the cross section at N<sup>3</sup>LO. This calculation is however extremely challenging. In fact, the computation involves  $\mathcal{O}(10^5)$  interference diagrams (for comparison only 1000 at NNLO), about 60 millions of loop and phase space integrals (47000 at NNLO) and about 1000 master integrals (26 at NNLO). The calculation was performed as an expansion around the threshold, where up to 37 terms in the expansion could be computed. This result is shown in the left panel of Fig. 2, while the right panel shows the dependence of the cross section on

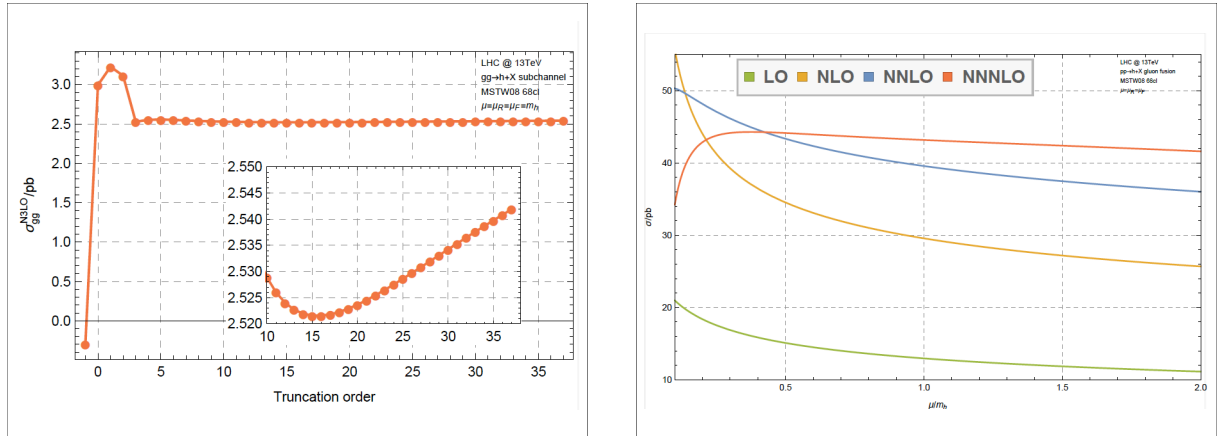


Figure 2 – Left plot: the N<sup>3</sup>LO correction from the  $gg$  channel to the total gluon-fusion Higgs cross section as a function of the number of terms included in the threshold expansion. Right plot: scale variation for the gluon-fusion cross section at all perturbative orders through N<sup>3</sup>LO.

the renormalisation and factorisation scales (varied together) at all perturbative orders through N<sup>3</sup>LO. The numbers to take home are that the N<sup>3</sup>LO corrections amount to about 2% at scale  $M_H/2$  and the residual uncertainty as estimated from scale variation is also about 2-3%. At this level of precision, other uncertainties (errors on parton distribution functions, treatment of electroweak corrections, exact top-mass corrections beyond the heavy-top approximation, top-bottom interference in loops...) now become all important. Updated predictions, that will also

include an independent scale variation, will provide a more robust estimate of the uncertainty due to missing higher orders. Nonetheless, the very little experience that we have with scale variation at this order may suggest a conservative approach.

### 3 Flavour

The flavour day was possibly the most exciting day of the conference because of the flavour anomalies observed recently at the LHC. Nazila Mahmoudi presented a concise introduction to flavour physics, recalling in particular the reasons why the flavour physics is so rich and interesting.<sup>4</sup> First of all, flavour physics is sensitive to new physics (NP) energies scales that are much larger than the collider energy, hence through flavour physics one could probe NP before it is observed directly in collider experiments. Furthermore, CP violation is closely related to flavour physics: the only source of CP violation in the Standard Model (SM) comes from the Cabibbo-Kobayashi-Maskawa (CKM) matrix, but for baryogenesis we know that we need other sources of CP violation. On top of this, there is the "SM flavour puzzle", i.e. the origin of masses and mixing of quarks and leptons, and the "new physics flavour puzzle", i.e. the mechanism protecting TeV-scale NP from causing large deviations from the SM predictions in the flavour observables that we have measured so far. Recently, there has been a lot of new data in this sector mainly from LHCb, but also from ATLAS and CMS. One of the new LHCb measurements concerns the CKM element  $V_{ub}$ . There has been a longstanding tension in  $V_{ub}$  (but also in  $V_{cb}$ ) from inclusive and exclusive decays. It was long believed that this measurement was not possible at LHCb, yet  $V_{ub}$  was recently measured there. This measurement, which was presented for the first time at the Electroweak Moriond meeting this year, seems to confirm the exclusive measurement.

Looking at other LHC data, almost all measurements are currently consistent with the SM. Yet, recently four hints for new physics in the flavour sector have been reported:

- the branching ratio  $H \rightarrow \mu\tau$  was measured to be  $(0.84 \pm 0.40)\%$  - rather than 0;
- in the decay  $B \rightarrow K^* \mu^+ \mu^-$  an anomaly was observed in an angular distribution called  $P'_5$ ;
- the SM branching ratio  $B_s \rightarrow \phi \mu^+ \mu^-$  at high invariant mass is above measurements;
- the ratio  $R_K \equiv \text{Br}(B^+ \rightarrow K^+ \mu^+ \mu^-) / \text{Br}(B^+ \rightarrow K^+ e^+ e^-)$  was measured to be  $0.75 \pm 0.10$ , rather than 1.

Adolfo Guevara focused on the anomaly in  $R(K)$  and showed that the discrepancy can not be attributed to long-distance, poorly-modelled effects.<sup>5</sup> While this is not an exciting finding, it is of course very important to have a solid estimate on long-distance effects. Ben Grinstein presented a very concise introduction to effective field theories (EFTs), and stressed that the reason for using EFTs is that they often have more predictive power.<sup>6</sup> This is due both, to the fact that they involve less free parameters and that you can often simplify (technically challenging) calculations. In particular, in terms of dimension 6 operators one can write the following contributions to the Lagrangian:

$$\mathcal{L}_{\text{eff}} = -\frac{G_F}{\sqrt{2}} \sum_{p=u,c} \lambda_{ps} \left( C_1 \mathcal{O}_1^p + C_2 \mathcal{O}_2^p + \sum_{i=3}^{10} C_i \mathcal{O}_i \right). \quad (1)$$

For the above anomalies, of particular interest are the electromagnetic dipole, the vector and axial-vector operators  $\mathcal{O}_7$ ,  $\mathcal{O}_9$  and  $\mathcal{O}_{10}$ , respectively

$$\mathcal{O}_7 = \frac{e}{(4\pi)^2} m_b [\bar{s} \sigma^{\mu\nu} P_R b] F_{\mu\nu}, \quad \mathcal{O}_9 = \frac{e^2}{(4\pi)^2} [\bar{s} \gamma^\mu P_L b] [\bar{l} \gamma_\mu l], \quad \mathcal{O}_{10} = \frac{e^2}{(4\pi)^2} [\bar{s} \gamma^\mu P_L b] [\bar{l} \gamma_\mu \gamma_5 l]. \quad (2)$$

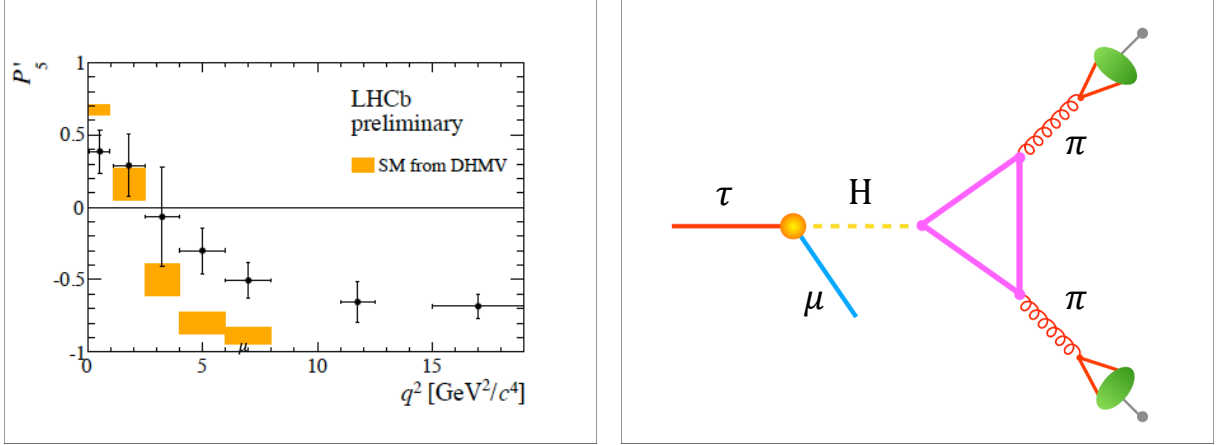


Figure 3 – Left plot: LHCb measurement of  $P'_5$  compared to SM predictions as a function of the momentum transfer. Plot taken from ref. <sup>7</sup>. Right plot: representation of the decay  $\tau \rightarrow \mu H (\rightarrow \pi\pi)$ .

Grinstein pointed out that taking into account all bounds, and assuming that NP effects are only due to scalar and tensor semi-leptonic operators one can constraint  $0.982 \leq R_K \leq 1.007$ . On the other hand, the measured value of  $R_K$  can be explained with a correction to the Wilson coefficient of the vector operator,  $C_9^{\text{NP}} \approx -1$  (other explanations for the measured value of  $R_K$  could also come from a  $Z'$  or leptoquarks).

Sebastian Descotes-Genon focused on the  $B \rightarrow K^* \mu^+ \mu^-$  anomaly, shown in Fig. 3 (left panel). <sup>8</sup> He explained how different kinematic regimes at low or high momentum transfer  $q^2$  imply a high or low recoil of  $K^*$  and hence NLO QCD factorisation or heavy quark effective theory become the appropriate tools to employ in the two regimes, respectively. He also explained how observables like  $P'_5$  are constructed in such a way as to cancel large uncertainties from soft form factors and that residual effects of power corrections are estimated to be about 10%. The conclusion of the study is that the LHCb measurement supports  $C_9^{\text{NP}} \sim -1$ , but there is room for NP also in other Wilson coefficients. Discussions about the accuracy of the theory predictions and the interpretation of data in terms of new physics are still ongoing.

Andreas Crivellin pointed out that all four LHCb anomalies could be explained in two models with gauged  $L_\mu - L_\tau$ : either a two-Higgs doublet-model (2HDM) with vector-like quarks or a three-Higgs doublet-model (3HDM) with gauged flavour dependent B-L charges. <sup>9</sup> Such a model predicts also a non-vanishing  $\tau \rightarrow 3\mu$  decay. Since the model has a point-like  $H\mu\tau$  vertex, a question was raised whether this is consistent with current limits on  $\tau \rightarrow \mu\pi\pi$ , which involves a Higgs exchange and the decay of the Higgs to two gluons through a top loop, illustrated in the right panel of Fig. 3. After a quick calculation Crivellin and Grinstein established that the model is still allowed. <sup>b</sup> This example illustrated how difficult it is today to design new models that explain possible anomalies but are not yet excluded by precision data. Still looking at extended Higgs sectors, Eibun Senaha presented a scale-invariant 2HDM with Coleman-Weinberg (CW) symmetry breaking, rather than spontaneous symmetry breaking as in the SM Higgs mechanism. <sup>10</sup> The model predicts deviations, for instance in the  $h \rightarrow \gamma\gamma$  decay and in the  $h h h$  coupling that are potentially detectable in future experiments. Another 2HDM, a Branco-Grimus-Lavoura (BGL) model, with naturally suppressed FCNC as a result of a symmetry of the Lagrangian was discussed by Gustavo Castelo-Branco. <sup>11</sup> In BGL models the entire flavour structure is controlled by the CKM matrix. 2HDM are an excellent framework to study NP in the scalar sector. For instance, it is not clear yet whether the discovered Higgs has small FCNCs. Hence, Branco pointed out that it is very important to search for flavour violation in the scalar sector. He stressed that theorists have been wrong many times, it is therefore important to look

<sup>b</sup>Greg Landsberg however pointed out that if you have four anomalies, and a model that explains all four of them, the model is wrong as at least one anomaly will surely go away.

without prejudice, in particular to look also for interactions or deviations that are not predicted in more common NP scenarios.

A last theory talk in the flavour session was given by Cai-Dian Lu, who pointed out that when the final state consists of two vector particles, an angular study of the vector's decay products provides an insight into the spin structure of flavour-changing interactions.<sup>12</sup> He stressed that, in particular, the meson decays  $B_{u,d,c,s} \rightarrow VV$  have a very rich phenomenology. Describing them is however difficult and many theoretical approaches exist, but most of them can not fully explain all measurements. He used a perturbative QCD approach, and stressed the important role of annihilation-type diagrams. Lu then presented many predictions and comparisons to data. Some looked very successful, others less so, however no theory uncertainties were given, so that it was difficult to draw conclusions.

## 4 QCD

Almost all talks in the QCD sessions were theoretical. The day was split into a more perturbative morning focusing on calculations of higher-order corrections, and a more non-perturbative afternoon, mostly involving new theoretical developments.

### 4.1 Perturbative QCD

First of all, it is important to remind ourselves why it is important to push the perturbative accuracy to higher orders. We have by now seen amazing results from Run I at the LHC, including competitive measurements of SM parameters (even of the strong coupling constant  $\alpha_s$ ), precision Higgs physics, jets spectra up to several TeVs, constraints on anomalous couplings, on NP models, on dark matter (DM) candidates and more, as summarised by Tom Le Compte.<sup>13</sup> Even better results are expected at Run II. An optimal use of the machine can be achieved when the experimental (statistical and systematic) and theoretical uncertainties are comparable. Currently, the use and interpretation of some cross sections is already limited by large theory uncertainties, mostly estimated via a variation of renormalisation and factorisation scales. Hence, it is mandatory to push the perturbative accuracy even further. Pier Paolo Mastrolia presented a beautiful review of modern methods for higher-order calculations.<sup>14</sup> He stressed the richness and power of factorisation, which is at the core of unitarity approaches and presented an interesting analogy between quantum mechanics and Feynman integrals. He then discussed a unitarity formalism, the Magnus Expansion, for multi-loop master integrals. Future directions include the treatment of multi-loop diagrams with internal masses and more legs and an automated analytic treatment of the one-loop case. Analytic results are in fact typically superior to numerical ones, since they are faster and numerically more stable.

Jonas Lindert showed novel one-loop methods at work: he presented the QCD and electroweak (EW) corrections to onshell  $W$  production in association with 1, 2, or 3 jets obtained using OPENLOOPS, MUNICH and SHERPA.<sup>15</sup> While NLO EW corrections might seem just a trivial extension of the QCD case, they are in fact technically much more complicated than just NLO QCD and involve a lot of subtleties. The phenomenological results for  $W$  plus multi-jet production that he presented are very rich, in particular one can observe a non-trivial dependence on the jet multiplicity.  $W$  plus multi-jet events play a key role for tests of the SM and for beyond SM (BSM) searches based on signatures with jets, a lepton and missing transverse energy (MET). One of the main outcomes of the results presented by Jonas is that EW corrections are important in the TeV region (where all order Sudakov effects should also be included). For the future, the plan is to include vector bosons decays, parton shower corrections and to extend multi-jet merging to NLO QCD+EW.

Beyond NLO corrections, Fabrizio Caola presented a brief review of the status of NNLO, including the motivation to push the perturbative accuracy to this order, the different methods used, the processes known or almost known (Higgs, Drell-Yan,  $t\bar{t}$ , single top,  $V+1$  jet, dijets,

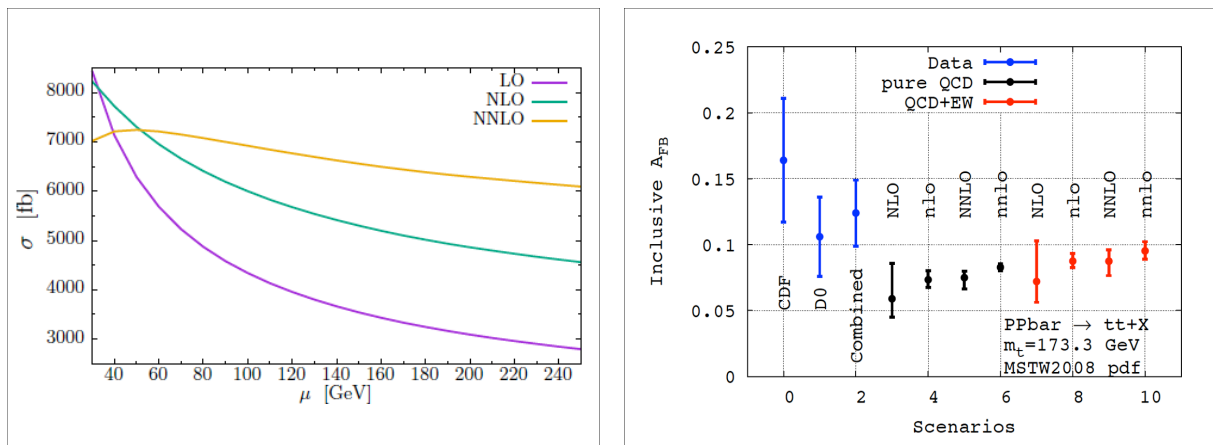


Figure 4 – Left plot: the Higgs plus one jet cross section at the 8 TeV LHC at various orders in perturbation theory as a function of the renormalisation and factorisation scale, both set to  $\mu$ . Jets are defined using the anti- $k_t$  algorithm with  $R = 0.5$  and  $p_{t,cut} > 30$  GeV. Right plot: data for the the forward-backward asymmetry from D0 and CDF (blue) compared to various theory predictions including only QCD corrections (black) or including both QCD and EW corrections (red).

dibosons,  $H+1$  jet).<sup>16</sup> The main message from his talk is very positive, i.e. that the NNLO technology is now ready to cope with LHC demands. However, because the phenomenological environment is so rich, it will not be enough here to provide numbers for cross sections or few distributions, and there will be a lot of pressure on the authors to release codes as soon as possible. He also showed results for Higgs plus one jet production at NNLO, which at the time of the conference were new and still unpublished. The NNLO corrections turn out to be sizable (of the order of 20% if the Higgs mass is taken as a central renormalisation and factorisation scale), and reduce the scale-dependence of the cross section, as can be seen from Fig. 4 (left). This was expected given the large corrections in the case of inclusive Higgs production, and emphasizes the importance of including NNLO corrections.

Another important NNLO calculation was presented by Michael Czakon, who discussed the long-standing tension between SM predictions and Tevatron measurements of the forward-backward (FB) asymmetry, for which plenty of tentative BSM explanations have been given in the past.<sup>17</sup> Recently, the SM theory prediction for the asymmetry has been upgraded to include full NNLO corrections. A limitation of the calculation is that the top quarks are stable, i.e. the result is fully inclusive in the top decay. One ambiguity that arises is due to the fact that the FB asymmetry is the ratio of the asymmetric over the symmetric cross section, hence one can choose to expand the ratio in powers of the coupling constant, or not. These two approximations are denoted by nnlo and NNLO in the right panel of Fig. 4, respectively. Furthermore, there is an ambiguity in how to combine EW and QCD corrections, either in an additive or in a multiplicative way. Fig. 4 (right) shows that there is now perfect agreement between the D0 result and NNLO theory, while the NNLO result is just  $1.5\sigma$  below the CDF measurement. The fact that the discrepancy in the asymmetry is not present any longer is mostly due to the updated measurement of D0, however the NNLO calculation was very important to confirm the robustness of the SM prediction. The calculation of the NNLO top cross section was presented two years ago, it took then a long time to provide predictions for the Tevatron asymmetry. One might then wonder whether it is realistic to expect distributions for the LHC in a reasonable amount of time, especially given the tension in the transverse momentum spectrum of boosted tops between next-to-leading-order (or LO matrix element plus parton shower generators) and ATLAS data.<sup>18</sup> Michael Czakon is now working on a completely new software based on a four dimensional subtraction scheme, which will be several orders of magnitudes faster than the first NNLO code for top-pair production.

While fixed-order calculations are very valuable in general, they are known to fail in particu-

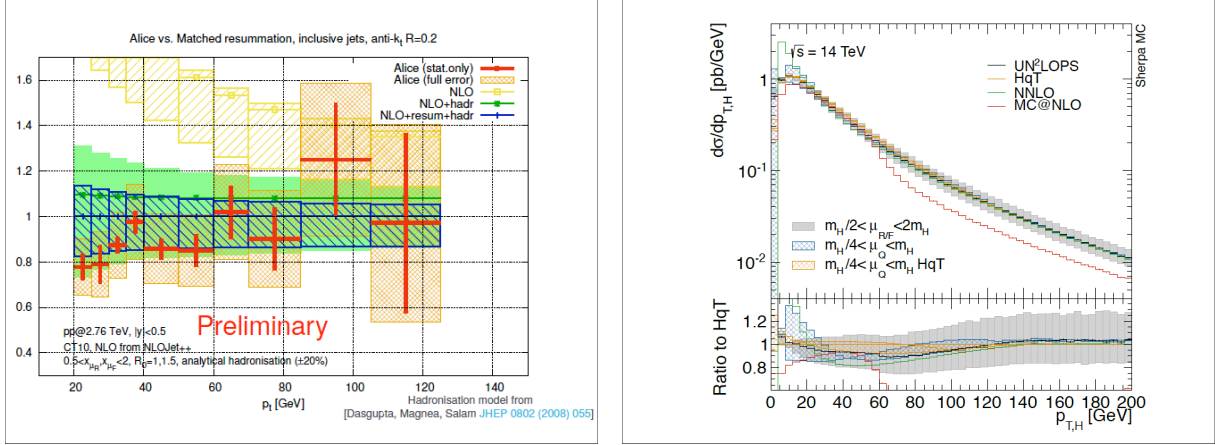


Figure 5 – Left plot: inclusive jet distribution measured at ALICE (red points and orange bands), compared to pure NLO with hadronisation corrections (green band) and a calculation that includes also  $\ln(R)$  terms to all orders (blue band). Jets are defined using the anti- $k_t$  algorithm with  $R = 0.2$ . A reduction of theoretical uncertainty can be observed. Right plot: the Higgs transverse momentum spectrum using the UN<sup>2</sup>LOPS method, compared to other calculations.

lar regions of phase space. In these regions, either parton showers or analytic resummations can be employed. In Higgs studies involving a jet-veto, it was suggested some time ago that there are potentially large logarithms related to the use of small jet radii. In fact, when the jet radius is small, the effect of emissions outside the jet, that reduce the energy, can become important. Because of the phase space constraints, this effect scales as  $\ln(R)$ . Frederic Dreyer explained that in a number recent jet-studies smaller jet-radii  $R$  are being used (e.g.  $R = 0.2$  in heavy-ions to mitigate pile-up, or in jet-substructure studies).<sup>19</sup> Frederic showed that a resummation of leading  $\ln(R)$  terms has been recently carried out using an evolution equation for the quark generating function. Fig. 5 (left) illustrates the reduced scale dependence that can be achieved once the  $\ln(R)$  resummation is performed for inclusive jet production. The plot also shows a comparison with experimental measurements from ALICE. There is good agreement within the currently large experimental errors. It is clear that this work will be even more relevant for future analyses, when more precise data will be available and the use of smaller jet radii will become more widespread in order to reduce increasing pileup contamination and to study more highly collimated jets.

Still in the spirit of improving fixed-order calculations, Stefan Prestel discussed going beyond NNLO by merging NNLO and parton showers.<sup>20</sup> This is important to have the best possible perturbative prediction and the fully exclusive description (i.e. the best of both worlds). NNLO was recently merged to a parton shower in the UNNLOPS approach for Drell Yan and Higgs production. Results for the Higgs transverse momentum distribution are shown in Fig. 5 (right). Currently, within this approach, the zero- $p_t$  bin is problematic, since the virtual correction is not spread by the parton shower, but it sits all at zero transverse momentum. In future, it would be desirable to extend the NNLOPS description to more complicated processes, however such a task is not trivial no matter which NNLOPS approach one considers.

While the calculation of higher-order terms in the perturbative expansion is obviously very useful to reduce the theoretical uncertainty, it is also important to have a solid procedure to estimate this residual uncertainty. This is obviously difficult, as the knowledge of the next term in the expansion would be required to provide a very reliable estimate of the theoretical uncertainty. A widely adopted procedure to estimate this uncertainty consists in varying the renormalisation and factorisation scales around a central value, which is chosen to reflect the hardness of the hard process. Emanuele Bagnaschi discussed how this scale-variation procedure has severe limitations in estimating the true theory uncertainty.<sup>21</sup> On top of this, the theory uncertainty has no statistical meaning, so it cannot be combined "properly" with experimental



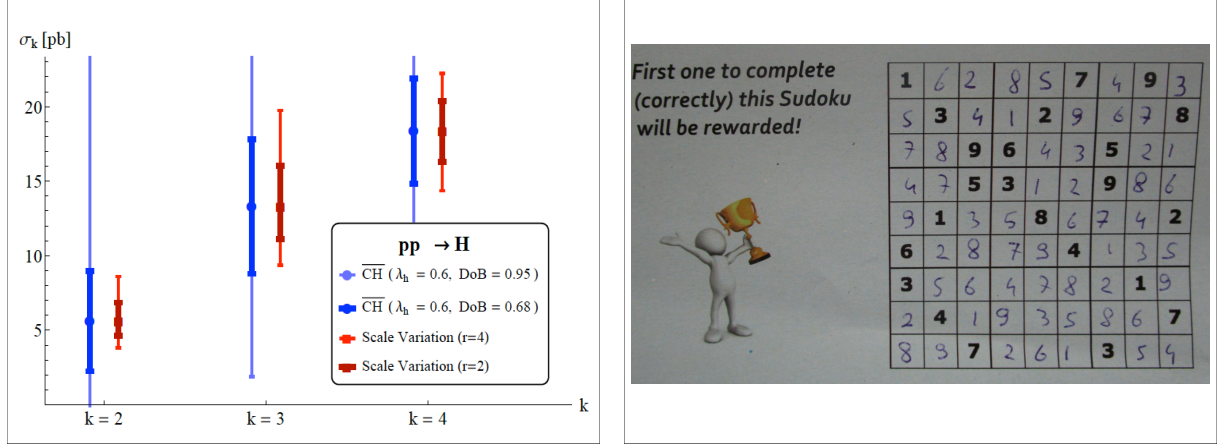


Figure 6 – Left plot: a comparison between two methods to estimate the theoretical uncertainties, scale variation (red) and the  $\overline{\text{CH}}$  approach. Right plot: a (non-standard) application of random matrix theory.

statistical uncertainties. In 2011 Cacciari-Houdeau (CH) proposed a Bayesian approach to estimate missing higher orders. Recently the CH method was modified to use a variable expansion parameter ( $\overline{\text{CH}}$ ). Furthermore, a first comprehensive set of more than 30 observables was used to compare the  $\overline{\text{CH}}$  method to standard scale variation, including, for the first time, hadronic observables. Fig. 6 (left) shows a comparison between the scale variation uncertainties and the  $\overline{\text{CH}}$  uncertainties for Higgs production.  $k$  denotes the order at which the calculation is performed. The scales have been varied by a factor 2 or a factor 4, while for the  $\overline{\text{CH}}$  approach, the 68% and 95% confidence intervals are shown. The general conclusion from this and other plots is that in many cases, scale variation appears to do a good job in estimating the size of the uncertainty. Furthermore, in most cases where the procedure fails, we believe we understand the reason. On the other hand there is value in having a quantitative, statistical meaning to any statement referring to theory uncertainties. In future, one can expect many valuable comparisons between the  $\overline{\text{CH}}$  approach and standard scale variation using new NNLO calculations that are becoming available.

Another source of theoretical uncertainty, beyond missing higher orders comes from our limited knowledge of the strong coupling constant. David D’Enterria pointed out that in fact  $\alpha_s$  is to date the least precise known of all couplings (known to about (0.5-1)%), and this impacts all LHC cross sections.<sup>22</sup> Furthermore, a very precise knowledge of the strong coupling is a key for SM precision fits and is relevant in BSM studies (e.g. for coupling unification at GUT). The current world average is  $\alpha_s = 0.1185 \pm 0.0006$ . David presented new fits of  $\alpha_s$  using the jet fragmentation function in  $e^+e^-$  and DIS data using an approximate NNLO calculation matched to NNLL. These fits give a value of the coupling of  $\alpha_s = 0.1205 \pm 0.0010$ . In future the plan is to extend the calculation to full NNLO+NNLL. Still, these fits are by far not trivial, as they require a careful treatment of the correlation between data and of heavy-quark thresholds.

#### 4.2 Less perturbative QCD

In-between fixed-order expansions and non-perturbative regions, there are regions of phase space where calculations are needed that resum large classes of corrections to all orders in the coupling constant, typically those accompanied by large logarithms. Many of these resummed calculations rely on the formulation of a factorisation theorem. Such a factorisation, while not necessary, turns out to be very useful in many cases, as it allows one to split the calculations into various elements that are simpler to calculate and that can be computed in one context and used in a different one. Mark Harley presented a clear introduction to some of these ingredients, i.e. Wilson lines, soft functions, (cusp) anomalous dimensions and webs.<sup>23</sup> The aim of his work is



a better description of universal soft singularities. Webs in this respect are very useful: they organise diagrammatic contributions to the exponent of the soft function, and one can show that all such contributions appear with connected colour factors. Subtracted webs are what remains in the exponent after the removal of multiple UV poles. Finally, multiple gluon exchange webs (MGEW) are subtracted webs with no gluon self-interaction (i.e. only dipole-like exchanges). It has been conjectured, and confirmed by explicit calculations in specific cases, that the integrand of MGEWs contains no polylogarithms, only logarithmic functions, each dependent on a single cusp angle. It is still an open question whether this always holds for MGEWs and it is not clear why does this happen. Furthermore, work is under way to extend current techniques to compute more general webs: in particular, results for completely connected diagrams at three loops were recently announced at the Radcor-Loopfest conference.<sup>24</sup>

Regarding the treatment of radiation from the initial state partons, all higher-order calculations mentioned so far rely now on collinear factorisation, which however does not work well when one incoming parton carries a very low momentum fraction. Sebastian Sapeta discussed an improved transverse momentum dependent factorisation for forward dijet production in dense (small  $x$ )-dilute (large  $x$ ) hadronic collisions.<sup>25</sup> This is the only existing approach which is valid in all regions of the transverse momentum of the target, from very high transverse momenta, where high-energy factorisation is usually applied, to very low ones, where collinear factorisation holds. Hence, this approach provides a robust framework for studies of saturation domains with hard probes. The final aim is to gain a better understanding of factorisation breaking and the nucleon structure.

While perturbative corrections can be calculated, non-perturbative corrections are usually just modelled. Sharka Todorova-Nova pointed out that the Lund string fragmentation model has been very successful. It has been implemented in Pythia and, after tuning, it describes data well in general. Still, it has limitations and some data is not well described by it. Hence, she presented a study of quantum properties of three-dimensional helix-shaped QCD strings.<sup>26</sup> The model is predictive after fixing two parameters for the string. According to Sharka, in the near future it will be possible to compare predictions from the model with upcoming measurements. Shi-Yuan Li pointed out that colour connections are the bridge between parton and hadron systems.<sup>27</sup> Four-quark systems ( $c\bar{c}b\bar{b}$ ,  $b\bar{b}b\bar{b}$ , etc.) have an intrinsic ambiguity in the colour wavefunction, which leads to different meson production. Li encouraged phenomenological studies in  $e^+e^-$  collisions to look and interpret different meson production as evidence of certain colour connections.

Various approaches to non-perturbative dynamics use symmetries and dualities to obtain results at strong coupling. Miguel Costa presented an AdS/QCD phenomenological model that matches well the intercept and slope of Donnachie-Landshoff pomeron.<sup>28</sup> The model is predictive, since everything in the model is fixed from soft pomeron exchange. A careful analysis of data for deep inelastic scattering (DIS), deeply virtual Compton scattering (DVSC) and virtual meson production (VMP) is hence interesting. Andrew Koshelkin looked at multi-particle dynamics and pion production using a flux tube (a compactification to two dimensions) and showed a comparison to ALICE data for the transverse momentum distributions in high-energy proton-proton collisions.<sup>29</sup> Giancarlo D'Ambrosio pointed out that soft wall models in holographic QCD have correct Regge trajectories but a wrong operator product expansion (OPE).<sup>30</sup> Hence, he presented a modified version of the dilaton potential that allows one to comply OPE. OPE is recovered by adding a boundary term. Low energy chiral parameters,  $F_\pi$  and  $L_{10}$ , are well described analytically by the model in terms of Regge spacing and QCD condensates.

We had a single lattice talk at the meeting on random matrix theory. Chiral Random Matrix Theory is a powerful mathematical tool to calculate eigenvalue correlations in the IR limit of QCD. The way it works is simply to replace the Hamiltonian with a Random Matrix with the same global properties. Once this is done, one can compute observables by averaging over ensembles. Here it is critical to identify what are the universal quantities (i.e. those that are

independent of the probability distribution). Savvas Zafeiropoulos considered explicitly the case of  $N_c = 2$  QCD and presented a study of the discretisation for  $D_5$  (i.e. the hermitian version of Wilson operator  $D_W$ ) and  $D_W$  itself.<sup>31</sup> In the future he plans to study the case of adjoint QCD, which has a different chiral symmetry breaking mechanism.<sup>c</sup>

## 5 New Phenomena

Unfortunately, no evidence for new phenomena has been seen in Run I at the LHC. Possibly the strongest motivation for physics beyond the SM is the astrophysical evidence for DM in galaxies and in cosmological observations. Leszek Roszkowski pointed out that the measured value of the Higgs mass of 125 GeV allows for rather heavy SUSY states, too heavy to be produced at the LHC. DM searches provide then important complementary bounds to collider searches.<sup>32</sup> In particular he emphasised the possible future role of the Cherenkov Telescope Array (CTA) experiment, a next generation ground-based very high energy gamma-ray instrument. Beside exploring the origin of cosmic rays and their role in the Universe, the nature and variety of particle acceleration around black holes, the CTA aims at searching for the ultimate nature of matter and physics beyond the Standard Model. For instance within the CMSSM, it will allow one to explore mass ranges (for  $m_0$  and  $m_{1/2}$ ) that are out of reach at the LHC, as can be seen from Fig. 7 (left). On the other hand, the existing tension with  $(g - 2)_\mu$ , if taken seriously, requires light-ish SUSY particles, which should be within LHC reach.

Another possible future experiment that is complementary to the LHC is SHIP (Search of Hidden Particles). Oleg Ruchayskiy pointed out that we might not have detected new particles at the LHC either because they are too heavy, or because they are light but very weakly coupled.<sup>33</sup> The first case, will be investigated by energy frontier experiments, currently the LHC Run II. The second option can be explored by going to the so-called intensity frontier. This is precisely what SHIP aims to do. The idea is just to take a highest energy/intensity proton beam, dump it into a target, followed by the closest, longest and widest possible and technically feasible decay tunnel. Oleg showed that for instance a Neutrino minimal SM, which addresses neutrino oscillations, DM, baryon asymmetry, and inflation, can be explored with SHIP. Similarly, SHIP can explore other models that involve very weakly interacting long lived particles including Heavy Neutral Leptons, right-handed partners of the active neutrinos, light supersymmetric particles (sgoldstinos, etc.), scalar, axion and vector portals to a hidden sector.

The complementarity between direct and indirect DM detection experiments and the LHC was also stressed by Greg Landsberg.<sup>34</sup> In fact, freeze-out, direct detection and collider production can be all represented using the same diagram and crossing the direction of time. DM is typically searched for at the LHC through so-called mono-X searches, i.e. the production of one (or more) SM particles or jets accompanied by a large MET that is attributed to DM particles escaping detection. Often DM searches use an EFT where the mediator has been integrated out. Greg pointed out that since the mediator is integrated out, the dynamics might not be properly described, and hence the interpretation of EFT results becomes problematic. Following the strategy used in SUSY searches, Greg suggested to use so-called simplified models. Here one identifies simple models and works out the signatures. The simplification limits the number of arbitrary parameters, still providing a robust benchmark.<sup>d</sup> The simplified model for DM searches used by Greg uses an  $s$ -channel spin-1 mediator, that interacts to DM and fermions. This is a four-parameter model. Extensions for instance to include the case of  $t$ -channel mediators, or spin-0 interactions are also possible. Fig. 7 (right) shows a comparison of EFT bounds (green) to the above simplified model assuming the spin-1 mediator to have pure axial-vector couplings. It is evident that in some regions of parameter space EFT results are too optimistic,

<sup>c</sup>An application of random matrix theory, in a different context, is illustrated in Fig. 6 (right panel).

<sup>d</sup>It is important to keep in mind that while simplified models are practical tools, they can exhaust their value as a benchmark at some point, as, I believe, is the case for the CMSSM now.

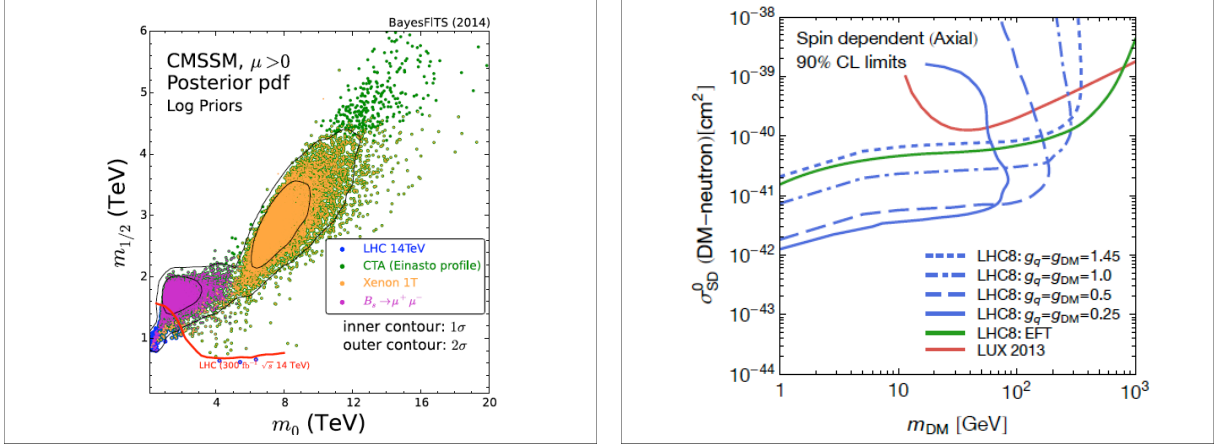


Figure 7 – Left plot: illustration of the range of the  $m_{1/2}$  and  $m_0$  plane that can be explored by various experiments. Right plot: bounds for the spin-dependent cross section that can be obtained within an EFT approach (green), or using a simplified model with different choices of the coupling of the mediator to quarks and DM (blue). Bounds from LUX (red) are also shown. Plot taken from ref. <sup>35</sup>.

in others they provide too loose bounds.

## 6 Heavy Ions

Our Friday started with a very comprehensive introductory talk on heavy ions (HI) by Carlos Salgado. <sup>36</sup> He pointed out that behind a simple QCD Lagrangian, there are very rich emerging phenomena, like asymptotic freedom, confinement, chiral symmetry breaking, mass generation, new phases of matter, and a very rich hadron spectrum. Some of the questions raised by observations can be further studied with heavy-ion collisions. For instance one can study the structure of the hadrons and nuclei at high energy, one can try to understand if the created medium is thermalised and what are the properties of the produced medium. In this context, for a long time proton-nucleon collisions (pA) were considered a benchmark point needed to subtract the background from nucleon-nucleon (AA) collisions. However pA collisions seems to have taken up an unexpected role since results for pA collisions turn out to have some features similar to those for AA collisions, in particular concerning the collective, hydro-dynamical behaviour. This raises the important question of whether such a small system can also thermalise. One of the standard probes of a hydro-dynamical behaviour is the so-called elliptic flow, i.e. the flow due to the fact that there is more momentum in the plane of the collision, compared to the transverse direction (a simple consequence of having a higher pressure gradient in the plane). Data are based on measuring two or more particle correlations. Recently, there has been a lot of theoretical work in trying to add fluctuations in initial conditions and in including viscosity corrections. Another standard tool is measuring jet quenching in medium. The idea here is simply that a medium suppresses the propagation of coloured particles, compared to the free propagation, hence this results in jet suppression. The simplest observable of jets in nuclear collisions is the measurement of the one-particle inclusive production at high transverse momentum. The effect of the surrounding matter can then be identified by the suppression of the signal, with respect to the proton-proton collisions, due to energy loss. A standard probe of medium effects uses the nuclear modification ratio, defined as

$$R_{AA} \equiv \frac{d\sigma^{AA}/dydp_T}{N_{coll}d\sigma^{pp}/dydp_T}, \quad (3)$$

where  $N_{coll}$  is a normalization factor computed in the Glauber model to allow the comparison with the proton-proton cross section. The suppression of high- $p_T$  hadrons was one of the first,

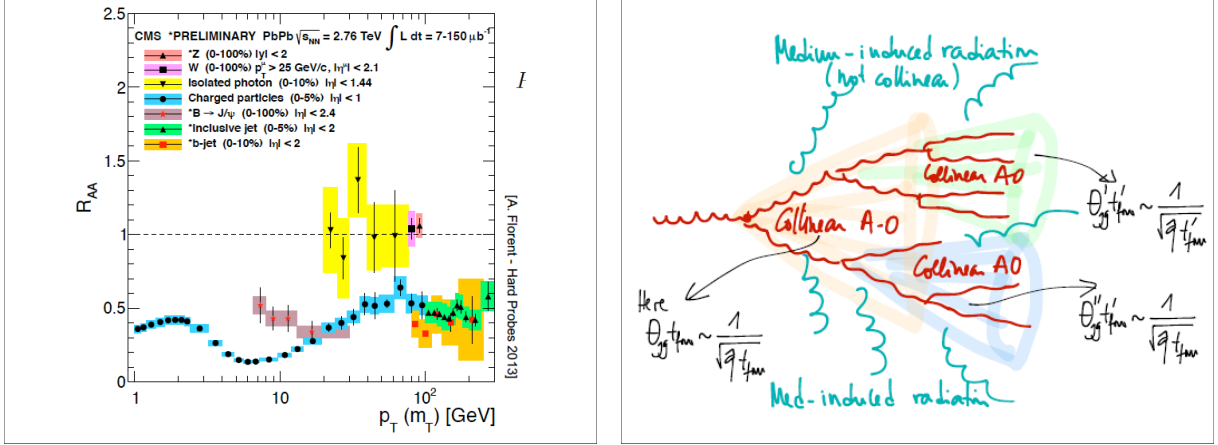


Figure 8 – Left plot: the nuclear modification ratio as a function of the transverse momentum. Right plot: a new picture of jet-quenching that involves two components, a vacuum-like, angular-ordered component (red) and a medium-induced, not collinear radiation (blue).

and also one of the main observations at RHIC. Fig. 8 (left) shows the effect of the suppression at the LHC, where the propagation of all particles interacting with the medium are suppressed. This can be seen from the fact that  $R_{AA}$  is smaller than one, while for isolated photons and EW bosons, that do not interact with the medium,  $R_{AA}$  is compatible with one. Carlos then presented a new picture of jet-quenching, illustrated in Fig. 8 (right), where the parton shower is composed of two overlapping components, which can be understood as a reorganisation of the jet into multi-jets, with vacuum-like collinear radiation, that effectively act as single emitters for the medium-induced radiation. It will be interesting to see how future measurements compare to this new picture.

When studying correlations, Matt Luzum pointed out that it is instructive to study two-particle correlation as a function of the transverse momentum vector of the particles.<sup>37</sup> In fact, the hydro-dynamic behavior imposes constraints on the momentum structure of two-particle correlation. One can define a full correlation matrix

$$V_{n\Delta}(p_T^a, p_T^b) = \left\langle \frac{1}{N_{pairs}^{a,b}} \sum_{pairs\{a,b\}} \cos n\Delta\Phi \right\rangle, \quad (4)$$

where  $N_{a,b}$  is the number of particles with momenta  $p_T^a$  and  $p_T^b$  in a given event,  $\sum_{pairs\{a,b\}}$  is the summation over all sets of these pairs, and  $\Delta\Phi = \Phi^a - \Phi^b$  their relative azimuthal angle. This quantity can be used to define

$$r_n \equiv \frac{V_{n\Delta}(p_T^a, p_T^b)}{\sqrt{V_{n\Delta}(p_T^a, p_T^a)V_{n\Delta}(p_T^b, p_T^b)}}. \quad (5)$$

Values of  $r_n = 1$  indicate no correlations, while  $|r_n| > 1$  are a sign of non-flow dynamics. CMS and ALICE data for  $r_2$  and  $r_3$  was also shown, however more data are needed, I believe, to draw solid conclusions.

Alexey Boyarsky discussed the chiral magnetic effect.<sup>38</sup> This is experimentally searched for at RHIC through a charge asymmetry of particles. It is usually widely discussed in the context of quark-gluon plasma and heavy ions. This effect is related to the fact that the SM plasma at finite densities of lepton and baryon numbers becomes unstable and tends to develop large-scale magnetic fields. The goal of Alexey's talk was to show that this effect is more general, and has to do with relativistic plasma of charged fermions (leptons and quarks). The conclusion is then that this effect can be important in other contexts whenever you have a relativistic magnetised plasma (such as in the early universe, in neutron stars, in astrophysical jets, and in quark-gluon

plasma). Elena Petreska discussed magnetic Wilson loops in the classical field of high-energy HI collisions.<sup>39</sup> In the abelian case, the Wilson loop measures simply a flux, while in the non-abelian case the Wilson loop obey area law for uncorrelated magnetic vortices, which is found to hold for large enough areas.

Alexander Bylinkin discussed the origin of the thermal component in transverse momentum spectra in high-energy hadronic collisions.<sup>40</sup> It is well-known that black holes radiate thermal radiation with a temperature that is proportional to the acceleration of gravity at the surface. Similarly, an observer moving with acceleration  $a$  detects a thermal radiation proportional to his acceleration. This is usually referred to as Unruh radiation. In both cases, the effect is due to the presence of an event horizon, for instance, in the accelerated frame, part of the space-time is causally disconnected from the accelerating observer. In the case of high-energy collisions, confinement is proposed to produce the effective event horizon for coloured particles. This results then in thermal hadron production with temperature of about 160 MeV. Bylinkin used these observations to present a two-component model for hadro-production. The two components are attributed to two different mechanisms: hard radiation with a saturation scale, and a thermal Unruh-like radiation. Bylinkin showed that there is good agreement between the available experimental data and the predictions of the model for rapidity distributions, average transverse momentum as a function of multiplicity, and transverse momentum spectra, which have been notoriously difficult to describe with standard approaches.

## 7 Looking ahead

I am very much looking forward to coming Moriond meetings with lots of exciting new experimental data. While we all have high hopes, we also wonder what will happen if, despite the tremendous experimental and theoretical efforts, we do find any sign of new physics in Run II at the LHC. It is important to remember that exploring the unknown is valuable in it's own right. Surely it will not be wise to draw too quick conclusions, but whatever happens, we will learn something by going to a new frontier (Run II, HL-LHC, FCC, ...).

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